FINAL REPORT

FULL FIELD VISUALIZATION OF SURFACE AND BULK ACOUSTIC WAVES

ONR CONTRACT N00014-82-K-0741-P04

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The objective of this research was to apply optical holographic techniques coupled with electronic signal and image processing to provide quantitative, full field measurements of acoustic wave disturbances. High speed pulsed holographic methods were developed to permit visualization of transient acoustic wave fields on the surfaces of solids and plates. In addition, it was possible to produce tomographic displays of acoustic energy flow in optically transparent fluids and solids. Special adaptations for heterodyne analysis made it possible to extract data from the holographic interferograms with sensitivities 900 times greater than conventional visual analysis.

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INTRODUCTION

The research summarized in this report was performed under Contract No. N0014-82-K-0741-P0004 covering the time period from September 1, 1982 through November 30, 1989. Throughout this period, the objective of the program was to explore means by which holographic methods might be employed to visualize, in full field, traveling acoustic surface and bulk waves. Improvements in both the time and measurement resolution of classical holographic methods were necessary in order to achieve these objectives. Dual reference beam holographic recording systems were designed to work with high speed pulsed lasers to obtain the desired objectives. By the conclusion of the program, it was demonstrated that holographic sensitivities to surface displacements as small as 6 angstroms could be obtained under very carefully controlled conditions. In general, however, displacement sensitivities below 60 angstroms were difficult to achieve. Nevertheless, the high speed holographic recording methods were shown to be effective means to visualize large amplitude surface acoustic wave displacements to such a degree that elastic properties in materials could be measured and defects in materials could be identified and located. Furthermore, it was possible to generate tomographic images of high energy acoustic waves propagating in air. Unfortunately, smaller amplitude acoustic displacements, such as those generated by piezoelectric transducers used for ultrasonic testing, were not reliably detected by holographic methods.

TECHNICAL BACKGROUND

The ability to map sensitively the full field of an acoustic wavefront propagating along the surface or through the bulk of a material should allow greater insight of the fundamental nature of acoustic wave propagation and, equally important, could serve as a useful tool for nondestructive evaluation of materials and structures. Information such as attenuation, scattering, diffraction, and energy flow can be obtained through visualization of a propagating acoustic field. In addition, structural defects such as cracks in metallic and ceramic materials or delaminations in laminar composites may be detected by observing the nature of alteration imposed on a propagating acoustic wavefront when it encounters such defects. The location, size, and, in some cases, the severity of the defect may be determined.

Unfortunately, full field visualization of a propagating acoustic displacement field is not easily obtained. Arrays of contact transducers have been contemplated for such use. However, their presence on the surface of the object or throughout the volume of some fluid changes the boundary conditions by loading the object surface or otherwise alters the acoustic environment of a test volume. The result is that the true nature of surface or bulk displacement associated with the propagation of an acoustic wave is distorted by the very presence of the transducers intended to detect and measure this displacement. For this reason, noncontact methods have been investigated to permit noninvasive and/or nonloading detection of acoustic displacement fields.

Optical interferometric techniques for detecting surface acoustic waves measure directly the normal surface displacement, slope (tilting), or velocity of a surface wave as it passes a single point. Some of these techniques offer extreme sensitivities for limited bandwidth, measuring surface displacements as small as 0.03 angstroms for 1 milliwatt of laser beam intensity and a detection bandwidth of 1 MHz. However, in order to visualize an entire sound field, the interferometer beam must be scanned over the object surface. Further, interferometric detection techniques are difficult to apply to diffusely reflecting surfaces of arbitrary shape.

Optical holographic nondestructive techniques take advantage of the ability of a hologram to record information about the three-dimensional shape of an object's surface. The holographically reconstructed image of the object is so faithful a representation of the object surface that it can be used as a reference against which light from the object itself can be compared interferometrically. The number and spacing of interference fringes observed when the two images are added is a function of the displacement of the object or portions of the object's surface from the time that the hologram was recorded. Depending on the optical geometry, each fringe represents a relative displacement of the surface on the order of 2500 angstroms or about one-half the wavelength of the light used to construct the hologram. Surface displacements may be observed in this manner as a result of whole body motion or local surface changes in response to an applied stress. Unlike the single point interferometers discussed previously, holographic interferometry is readily applied to arbitrarily shaped diffusely reflecting objects. Unfortunately, the ability to view in full field

displacements on a diffusely reflecting object comes at the cost of decreased displacement measurement sensitivity when compared with single point interferometers.

To understand the problems associated with holographically recorded acoustic field information, it is important to realize that a hologram is itself a record of the interference between an unmodulated reference beam and an object beam which has been modified by reflection from the object's surface. Microscopic examination of an exposed and developed hologram reveals recorded fringes at a rate of about 1000 per millimeter. The fringe rate is not constant over the entire hologram but varies as a function of the modulated object beam. This complex fringe pattern serves as a diffraction grating when it is reilluminated by a replica of the original reference beam. Under the proper conditions, a replica of the original object beam is then "diffracted out" of the illuminating reference beam to produce an image of the object in three dimensions. The efficiency with which a hologram is able to reconstruct an object beam is dependent largely upon the clarity and contrast of the recorded high frequency fringe pattern. Consequently, any vibration of the optical components or motion of the object during the exposure tends to blur the recorded fringe information and thereby reduce the hologram efficiency. If the direction of the object velocity vector is known and the appropriate optical geometry is used, resolution of front surface detail has been predicted for velocities of 90 kilometers per second with exposure time of 25 nanoseconds. Throughout this program, traveling acoustic waves (velocity approximately equal to 5 kilometers per second) were holographically recorded using a pulsed Nd:YAG laser with a pulse duration of about 9 nanoseconds. Other optical geometries may be used to permit recording objects with random velocity vectors.

Having established that with appropriate optical geometry and laser pulse width, it is possible to record high speed transient surface displacements, there still remained several issues which needed to be addressed before holographic recordings could be made so that useful data could be obtained regarding the nature of a propagating acoustic wave field. To understand these issues, consider first the characteristics of a double exposure hologram constructed in order to visualize a traveling wavefront. The first exposure was made to record the object surface at rest. The second exposure recorded the object surface while an acoustic wavefront was propagating across the surface. A typical recording geometry is one in which a

collimated reference beam illuminates directly the holographic film plate and combines with light scattered by the object's surface from an illumating laser beam. Upon development of the film and reillumination by a replica of the original reference beam, two images are reconstructed which interfere, generating fringes wherever the surface was displaced by an amount greater than one-half of the optical wavelength (i.e., one fringe for every 2500 angstroms of displacement). Flexural plate wave modes (asymmetric lamb waves) with amplitudes well in excess of that necessary to produce holographic fringes were generated both by direct laser excitation and by laser detonation of small amounts of chemical explosives.

Neglecting for the moment the apparent inability of holographic methods to detect and measure low amplitude acoustic waves, there are basic experimental difficulties associated with making holographic measurements even of large amplitude transient acoustic events. One difficulty is the coordination between the timing of the acoustic event and the "firing" of a pulsed laser used to make holographic recordings. A second difficulty bears on the first and results from the need to use relatively high energy pulsed lasers to make holographic recordings. This need arises from the fact that the resolution of holographic films may exceed 2500 lines per millimeter 1 to 2 orders of magnitude higher than conventional photographic films. Owing to this extremely high resolution, the sensitivity of the film is correspondingly reduced so that much higher exposures are required for holographic films that for photographic films in order to produce the same change in optical density. For acoustic studies, it is desirable to produce holographic exposures in 10 to 50 nanoseconds, therefore, the intensity of the recording light, which exposes the film during that brief period, must be extremely high. For this reason, solid state lasers, such as ruby and frequency doubled Nd:YAG, are used.

In general, "firing" such a solid state laser is a two-stage process. First, high intensity xenon flash lamps are fired by discharge of a capacitor bank. The duration of this firing may range from 1 or 2 milliseconds. At some instant several tens of microseconds following the onset of flash lamp pumping, a Q-switch within the laser cavity is opened to permit a very brief pulse of laser light to be emitted. Consequently, one may not use the initiation of an acoustic source to trigger directly a pulse from the recording laser without encountering this delay between the flashlamps and the Q-switch pulse. For acoustic

velocities in the neighborhood of 5 kilometers per second, propagation distances from 100 to perhaps 500 millimeters may be traversed before the recording laser can flash. For this reason, it was found to be more reliable and useful to use the laser itself as a means to trigger the acoustic source. A frequency-doubled Nd:YAG laser system was modified to permit double pulsing of the cavity Q-switch within a single discharge time of the flash lamps. For the laser used throughout this program, a pulsed duration of 9 nanoseconds could be generated with separations between pulses ranging from 10 microseconds up to approximately 100 microseconds. Shorter pulse separations were not possible since at least 10 microseconds were required to reinvert the electron population in the laser rod before a second pulse could be delivered. The recording sequence for double exposure holograms, then, was one in which the first pulse from the laser was used both to record the resting state of the test volume or object surface and to initiate an acoustic event either by direct heating of the material or indirectly by detonating a small amount of a chemical explosive. The second pulse from the laser could be delayed appropriately from the first one in order to permit propagation of the acoustic wavefront by a pre-determined amount. At that point, a second holographic recording was made on the same film plate. This method of using the first pulse from the laser either as an acoustic source or to trigger an acoustic source was used throughout virtually all of the experiments in this program. With this procedure, it was possible to produce holographic interferogram images of large amplitude acoustic waves where multiple fringes occurring in the double exposure holographic image of the object surface could be interpreted as microscopic contours with intervals corresponding to about 2500 angstroms.

Although, as will be discussed in the "Accomplishments" section, the double exposure technique just described proved very useful for visualizing flexural modes in alloy and composite plates, it had two rather severe shortcomings. These shortcomings made it difficult to interpret holographic information collected by this method for smaller amplitude displacements or for acoustic modes where the nature of the displacements could not be predicted. The difficulties arose from the fact that conventional double exposure holographic interferograms provide displacement contour information which may be interpreted perhaps to one-half of one contour (or about 1250 angstroms) but which also are ambiguous with regard to the direction of the displacement being contoured. Therefore, neither the fine detail of the surface displacement nor the

absolute directional sense of the displacement could be ascertained without some apriori understanding of the acoustic displacements expected.

One technique for measuring the magnitude and direction of surface displacements with sub-fringe sensitivity from a recorded holographic interferogram is heterodyne holographic interferometry. The heterodyne technique uses two angularly separated reference beams to record and read out the hologram. During the recording of the double exposure hologram, one reference beam is used for the first exposure and the other for the second. On play back, each reference beam reconstructs the object beam corresponding to the first and second exposures, respectively. With either one or the other reference beams reconstructing the hologram, one observes simply an image of the object. With both reference beams illuminating the hologram, both object states are reconstructed so that one observes what appears to be a conventional holographic interferogram. A significant difference exists, however, in this dual beam case since, by changing the phase or frequency of one of the reference beams relative to the other during the reconstruction process, one can cause the observed fringes either to shift or to move continuously. For true heterodyne reconstruction, Bragg cells are inserted in each of the reference beams and are used to shift the beams at slightly different frequencies, causing the fringes to move so that the intensity at each point on the image fluctuates periodically at the difference frequency of the two reference beams. The intensity variations at any point may be detected and compared in phase with a reference signal from some other fixed point on the image. The phase difference then may be measured and recorded for each spot in the image. A 360° phase difference is equivalent to 1 fringe displacement observed in the conventional holographic interferogram. Thus, the measurement resolution of the heterodyne system is limited only by the stability of the optical setup, spatial bandwidth of the imaging system, and the accuracy with which phase differences can be measured. Furthermore, the direction of the measured displacements can be determined directly by the direction with which the measured phase shifts from one point to the next in the image field. The heterodyne technique, therefore, is inherently direction sensitive, independent of brightness variations across the image, unaffected by variations in fringe contrast, and provides the same accuracy at any location on the image. In our own program using a vector lock-in amplifier for electronic phase measurement, surface

displacement accur~ ɔs to about 1/900 of a fringe, or about 3 angstroms, was demonstrated. As mentioned previously, however, this high degree of measurement sensitivity was not easily duplicated for a broad range of object types and surfaces. In general, measurement accuracies were almost an order of magnitude poorer.

Unlike single point interferometric techniques, limitations to measurement sensitivity do not arise from shot noise and other temporal noise sources. Instead, in the holographic case, there is a spatial measurement uncertainty which varies as a function of position in the image plane and arises from random phase contributions of individual speckle within the area of a single pixel. At any given pixel, one can measure the electronic phase with very high precision. However, the nature of contribution made by individual speckles at that image point lends considerable uncertainty to that measurement. By increasing pixel size to incorporate greater numbers of speckle, one is able to reduce the statistical error. Thus, with a relatively large detector area, so that 40,000 to 100,000 speckles may be included, the accuracy with which displacement measurements can be made approaches the limits imposed by temporal noise sources. Even these temporal sources, especially shot noise, are a greater factor in holographic than they are in conventional single point interferometric methods, owing to the fact that the light intensity from the laser is now distributed over an entire image field rather than concentrated at a single point. Thus, the intensity from any single point in a hologram is much smaller than the signal intensity received from light bounced directly off of the surface into a real time single point interferometer. In principle, however, with very high holographic reconstruction efficiencies to ensure high image intensity, surface displacements with low spatial frequency, and large detector apertures, it should be possible for heterodyne holographic interferometry methods to approach those sensitivities observed with single point interferometers.

An additional problem with the heterodyne holographic scheme just described is the length of time necessary to acquire a single image of a displaced surface. A far more rapid means to extract sub-fringe displacement information is quasi-heterodyne holographic interferometry or phase step holographic interferometry. A holographic exposure using dual reference beams is again made in a manner identical to that by which holograms were recorded for heterodyne analysis. In the phase step method, however, instead of imposing a frequency shift between the two reconstructing reference beams, a phase shift is imposed

which causes a corresponding displacement of the fringes observed in the interferogram image. Since it can be shown that the fringe location is a function of two other variables, namely, object brightness and fringe contrast, in addition to the displacement information which is desired, one can impose three known phase shifts and record each interferogram image in a video digital memory. Since for each pixel three intensities are recorded as a function of three known phases, there exists for that pixel a system of three equations in three unknowns which may be solved directly for either object brightness, fringe contrast, or, most importantly, surface displacement. Although in principle the phase step method is limited also by speckle and, ultimately, shot noise, it is in practice limited by the inherent noise of the video detector. Nevertheless, it is not difficult to obtain measurement precision to 1/50 of a fringe, or about 50 angstroms. Owing to its speed and convenience of use, quasi-heterodyne, or phase step, holographic interferometry was used more frequently throughout the project than was true heterodyne holographic interferometry.

Research efforts through the first years of this program established the fact that pulsed holographic interferometry provided sufficient time resolution to study propagating surface acoustic waves and was demonstrated to do so for acoustic field velocities of at least 6 kilometers per second. Also developed was new technology to permit dual reference recording of holograms so that sub-fringe displacement resolution could be obtained. In the final years of the program, these efforts were extended to investigate transient acoustic fields propagating through bulk materials using transparent fluids and solids as test specimens. As had been the case with surface wave mapping, pulsed holographic recording techniques were used. In this new application, however, the holograms provided high temporally and spatially resolved records of the integrated optical delay of light passing through a specimen as modified by local variations in acoustic field intensity through a piezo-optic effect. Subsequent analysis of these holograms was made using scanning heterodyne and phase step interferometric techniques so that the integrated delay could be read out for any optical path through the test volume. These data, along with those corresponding with other "views" through the specimen, were then processed on a digital image processing system using computerized tomography algorithms.

Prior to this program, efforts using light diffraction methods to tomographically map sound fields in transparent media had been restricted to time averaged studies of periodic acoustic signals for transducer characterization and calibration. The calculation of the integrated phase delay for a ray of light passing through a test medium has been based on diffracted light intensity measurements and mathematical models which describe the diffraction expected under certain conditions. If such conditions can be met or assumed, the model can be "inverted" to yield the sound pressure levels within the medium giving rise to the measured diffraction pattern. (This is in contrast to the holographic method developed where integrated optical phase delay, rather than intensity, is measured.) First among the list of mathematical predictors of light diffraction from acoustic waves is the work by Raman and Nath. Their work describes the intensity of light in the diffraction orders for a narrow beam of light diffracted by a sinusoidally periodic tranverse acoustic field. This intensity variation is described as a Bessel function of order equal to the optical diffraction order and whose argument is the integrated optical phase delay through the medium. Therefore, by measuring the intensity of the light diffracted into one of the orders, one can compute the phase delay and, ultimately, the effective (integrated) acoustic field strength along that optical path. For higher amplitude waves with significant harmonic content, B. D. Cooke and others have applied Fourier theory or diffraction theory to arbitrary periodic phase gratings to determine the field strength for each harmonic component. Alternatively, power series models have been used when the shape and symmetry of the sound field is known. All of these theories become invalid or increasingly complicated if pure phase grating assumptions of Raman and Nath can no longer be assumed. Furthermore, with the exception of gated RF sources, none of these sources have been applied or are experimentally practical for investigating pulsed single event acoustic sources.

The fact that pulsed sources present a difficult challenge to conventional light diffraction techniques is not to say that light passing through pulsed acoustic beams is not meaningfully modulated by the acoustic pulse. While previous workers have sought to determine phase delay information from the intensity of the light in diffracted orders, all the theories support the fact that this information should be available directly by measuring the phase delay in the undiffracted (0-order beam). With pulsed heterodyne holographic methods, it is possible to capture and analyze the probing light beam in order to determine its integrated phase delay

through the medium of the pulse. Difficulties arise only in the ability to collect the appropriate number and angular range of views through the sample volume necessary to back project the integrated data into a tomographically reconstructed image. For acoustic fields with high axial symmetry, meaningful information regarding the distribution of sound pressure levels in the acoustic field may be obtained with a very limited number of views.

ACCOMPLISHMENTS

1. Transient Lamb Wave Velocity Determination Using Holographic Mapping of Spatial Features of Propagating Waves

To demonstrate that adequate temporal resolution could be obtained using holographic recordings by a 9 nanosecond pulse duration laser, a study was undertaken to map transient plate waves in a variety of specimen materials. The project used the double-exposure holographic technique with which group velocities of transient antisymmetric lamb waves were computed using only spatial features of the propagating wave form. The results obtained were shown to be in good agreement with those predicted from elastic theory dispersion relationships for thin plates. The technique was applied successfully to brass, aluminum, and graphite epoxy laminate composite specimens over a range of thicknesses. The same measurement criteria were used for each sample. In addition to obtaining quantitative estimates of elastic properties, the method proved to be an effective means of detecting sub-surface defects, delaminations, and gross anisotropy.

2. Triple-Exposure Pulsed Holographic Recording for High Measurement Resolution Analysis of Transient Phenomena

Having established that pulsed holographic methods could be used to provide sufficient temporal resolution, a triple-exposure method using two reference beams was proposed and implemented successfully, thereby permitting heterodyne and phase step analysis of high speed holographic interferograms. The heterodyne method using double-exposure dual reference holography had been demonstrated and well documented in the literature for static measurements. However, in the high speed pulsed recording case, only 10 to 100 microseconds can elapse between holographic recordings. Electro-optic switching was

investigated initially as a means to change the illumination angle of the reference beam between exposures. While some degree of success was obtained, the method was relatively expensive and difficult to implement. In contrast, the triple-exposure method allowed for a single reference exposure to be made using one of the reference beams without exciting an acoustic wave on the object. Subsequently, two addition exposures of the holographic plate were made using a conventional double-exposure pulsed holographic recording method and a second reference beam angle. This triple-exposure holographic image could then be processed using heterodyne or phase step methods. In instances where the laser intensity of the first of the high speed exposures could be kept small relative to the second high speed exposure, only a small measurement error was obtained relative to a more conventional double-exposure dual reference beam heterodyne holographic analysis.

3. Film and Wavelength Effects on Heterodyne Holographic Measurement Accuracy

Although heterodyne holographic measurement sensitivities as small as 6 angstroms had been demonstrated in our own laboratory. Such sensitivities were difficult to achieve and were only barely sufficient to resolve small elastic wave displacements in solid materials. In the high speed case, holographic recordings were made at a wavelength corresponding to that of a frequency doubled Nd:YAG laser (λ = 532 nanometer) and were most easily reconstructed using an Argon ion laser (λ = 514.5 nanometer). The effects of limitations imposed by film granularity and inaccuracies resulting from differences in the recording and reconstructing wavelengths were analyzed in order to determine whether or not measurement resolution could be further improved. In brief, it was determined that so long as film dimensions and the numerical aperture of the holographic imaging system are sufficiently large, the measurement inaccuracy contributed by resolution limitations of commercially available holographic films was not a primary limiting factor in overall measurement resolution. On the other hand, wavelength variation between recording and reconstruction were a major source of phase measurement uncertainty. It was proposed and demonstrated through the course of these studies, however, that if precise collimation of the reference beams could be maintained for both recording and reconstructing wavelengths, this source of measurement error was eliminated entirely.

4. <u>Tomographic Reconstruction of Holographic Images of Transparent Materials</u>

Heterodyne holographic interferometry was applied to imaging disturbances in transparent materials as opposed to diffusely reflecting solid objects by passing the beam through the test volume and recording changes in phase resulting from variations of pressure. In this final phase of the program, tomographic images were obtained of the acoustic wave resulting from the explosive shock produced by laser detonation of 1 milligram amounts of silver acetylide. Full field holographic images of the explosion event look very similar to what one might expect to see on a Schlieren recording of the same event. That is to say, the observed image is a function of the integrated effect of light passing through the test volume where pressure variations are inhomogeneously distributed. By using multiple views through the test volume afforded by the holographic recording method, and combining this with phase stepping, integrated phase delay data have been processed by tomographic algorithms to produce detailed maps of the variations of pressure within the test region. Even with multiple holographic plates surrounding the test volume, however, it was difficult to get a full range of views over a 180° arc around the test volume. These missing views degraded the quality and accuracy of the tomographic reconstructions in all but those cases in which the object or the acoustic event was highly symmetric. This problem of tomographic reconstruction from incomplete data sets is an issue of current interest and activity in both the medical and industrial communities interested in x-ray tomographic imaging.

<u>Students Supported</u>

James W. Wagner, Ph.D. 1984, "Heterodyne Holographic Interferometry for Visualization of Surface Acoustic Waves"

Louis C. Phillips, Ph.D. 1986, "The Investigation of the Fundamental Limits of Heterodyne Holographic Interferometry with the Application of Imaging Laser Generated Lamb Waves"

Michael J. Ehrlich, M.S.E. 1989, "Materials Characterization Using Holographic Mapping of Transient Lamb Waves"

Andrew D. W. McKie, Post-Doctoral Fellow 1989-1990

Publications Resulting from Work Performed Under This Program

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